

X-RAYS FROM DISK GALAXY HALOS, $\text{Ly}\alpha$ FROM FORMING GALAXIES, AND THE $Z \sim 1$ TF RELATION

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Abstract Extended, soft X-ray emission from the halo of a very large disk galaxy has been detected. The luminosity and surface brightness distribution is in excellent agreement with predictions by recent, cosmological galaxy formation models. Predicted $\text{Ly}\alpha$ emission, associated with “cold” accretion of filamentary gas onto galaxies, is discussed in relation to $\text{Ly}\alpha$ “blobs”. Finally, the predicted evolution of the Tully-Fisher relation, going from $z=0$ to 1, is discussed in relation to recent observations.

Keywords: Cosmology – Galaxies – Numerical Simulations

1. X-ray emission from disk galaxy haloes

Disk galaxies continue forming to the present day, as evidenced by, e.g., infall of high-velocity clouds and satellite galaxies. Self-consistent models of disk galaxy formation predict that, at present, part of the inflowing gas originates as hot and dilute, low-metallicity halo gas, slowly cooling out and accreting onto the disk (e.g., Abadi et al. 2003, Sommer-Larsen et al. 2003, Governato et al. 2004, Robertson et al. 2004). The X-ray luminosity of the hot halo is predicted to increase strongly with galaxy mass, and the haloes of the most massive galaxies should be detectable (Toft et al. 2002, Rasmussen et al. 2004). Searches for this hot halo gas have so far failed to detect such soft X-rays, challenging galaxy formation theory. Moreover, it has been suggested that for galaxies of total mass less than a few times $10^{11} M_{\odot}$, most gas stays cold during the accretion onto the galaxy (apart from a very transient radiative shock phase, e.g., Birnboim & Dekel 2003; Dekel & Birnboim 2005; next section). This may result in reduced halo X-ray emission. On the other hand, the recent detection of a warm-hot phase of the intergalactic medium shows the presence of a reservoir of hot and dilute gas at galactic distances (Nicastro et

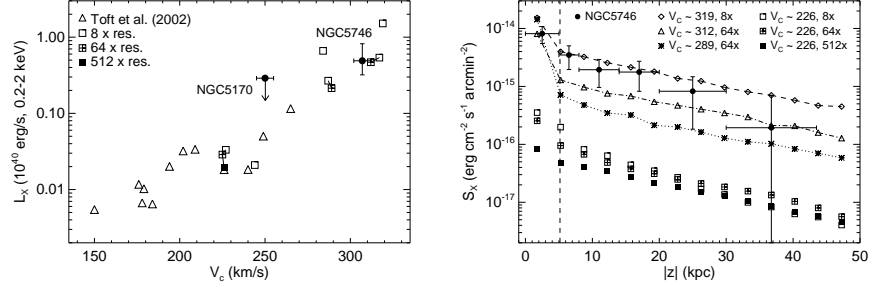


Figure 1. Left: Predicted and observed 0.2-2 keV luminosities of X-ray haloes as a function of disc circular velocity. All X-ray luminosities have been calculated within the same physical aperture as used for NGC 5746. The filled circles are from the observations of NGC 5746 and NGC 5170 ($1-\sigma$ upper limit of $L_X < 2.9 \cdot 10^{39}$ erg/s, 0.3-2 keV), while other symbols are the predictions for simulations with a range of different resolutions and circular velocities: Triangles are for simulations with low-metallicity chemical composition while squares are for simulations with self-consistent chemical evolution run at 8, 64, and 512 times the original resolution (Sommer-Larsen, Gotz and Portinari 2003) corresponding to gas particle masses of $7.5 \cdot 10^5$, $9.4 \cdot 10^4$ and $1.2 \cdot 10^4 h^{-1} M_\odot$, respectively ($h=0.65$). Results from simulations re-run at higher resolution are connected with lines. Open squares, except the simulated galaxy with a circular velocity of ~ 225 km/s, are for simulations run with a universal baryon fraction of 0.15. All other simulations were run with a baryon fraction of 0.1. Right: Predicted and observed surface brightness profile of X-ray haloes as function of the distance to the disc mid-plane. Filled circles are NGC 5746 data while other symbols mark simulations with different resolutions and circular velocities. The vertical dashed line indicates D25 of NGC 5746.

al. 2005). Furthermore, absorption of the OVI line in quasar spectra (Wakker et al. 2004), and the head-tail structure of some high-velocity clouds in the halo of the Milky Way (Bruns et al. 2000) provide circumstantial evidence that the Milky Way is surrounded by an extended hot halo.

As a test of current disk galaxy formation models we used the Chandra X-ray telescope to study the most promising candidate spiral galaxy for detecting halo X-ray emission, NGC 5746. We also studied a similar, but less massive galaxy, NGC 5170, as a test of our procedure. The galaxies are massive and nearby (NGC 5746 is an SBb galaxy at $d=29.4$ Mpc and has $V_c=307 \pm 5$ km/s; NGC 5170 is an Sc galaxy at $d=24.0$ Mpc and has $V_c=250 \pm 5$ km/s). Both galaxies are quiescent, showing no signs of either starburst activity, interaction with other galaxies, or an active galactic nucleus. The disks of the galaxies are viewed almost perfectly edge-on.

Diffuse, soft X-ray emission extending more than 20 kpc from the stellar disc was detected around NGC 5746. A total of about 200 net counts in the 0.3-2 keV band were detected from the halo of NGC 5746, corresponding to a $4.0-\sigma$ detection. The same observing technique and data analysis revealed no diffuse emission around the less massive galaxy NGC 5170. Moreover, from

Fig.1 it follows that the agreement between observations and models is very good. Full discussions of the results are presented in Pedersen et al. (2005), and Rasmussen et al. (2005).

2. “Cold” accretion, and Ly α properties of forming galaxies

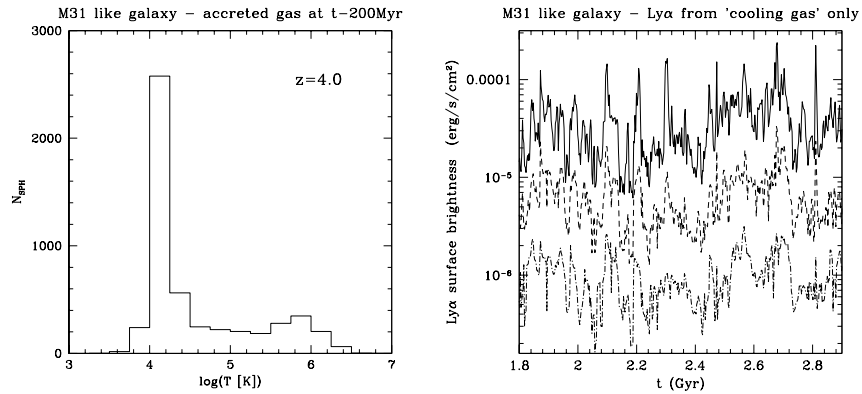


Figure 2. Left: Temperature distribution of gas particles, prior to accretion onto a number of starforming proto-disks in a M31 like proto-galaxy. Shown is (at a time 200 Myr before the $z=4$ frame) temperatures of gas particles, which at $z=4$ are located in the starforming proto-disks at densities $n_H > 10 \text{ cm}^{-3}$, and which 200 Myr prior to this have not been accreted onto the proto-disks yet. Right: Ly α surface brightness of “cooling” radiation from the region around a M31 like proto-galaxy at $z \sim 3$, versus time. Top curve shows the peak surface brightness; second and third averages over circular regions of radii 10 and 20 kpc, respectively, centered at the position of the peak Ly α surface brightness.

Not all gas, ending up as cold and star-forming in galaxies, has been shock-heated to temperatures $T \sim 10^6 \text{ K}$, and then (considerably) later accreted onto the galaxy. Rather, some of the gas is accreted at densities and rates, such that accretion shocks are strongly radiative, and the gas remains at $T \sim 10^4 \text{ K}$ during the accretion, cooling mainly by abundant Ly α emission (previous section). So, although most of the Ly α photons produced in young galaxies originate from photo-ionized HII regions around young, massive stars, a fraction of the Ly α photons produced in and around the galaxies originate from cooling, almost neutral gas – we find this fraction to be typically of order 10%. In Fig.2 (left) is shown, for a high-resolution galaxy formation simulation (2.2 million particles, $m_{\text{gas}} = 9.4 \cdot 10^4 h^{-1} M_{\odot}$), the temperature distribution of gas before it is accreted onto the proto-disks of a M31 like proto-galaxy, at $z=4$. As can be seen, at this redshift, the majority of the gas is, in fact, accreted “cold”.

Can Ly α emission associated with “cold” accretion be observed? In recent years a number of so-called Ly α “blobs” have been detected (Keel et al. 1999, Steidel et al. 2000, Francis et al. 2001, Matasuda et al. 2004, Palunas et al. 2004, Dey et al. 2005). These are systems with spatial extents of up to 100 kpc, and Ly α luminosities of up to 5×10^{43} erg/s. In all cases, but one (see below), counterparts (like optical, IR, X-ray or radio) have been detected. Various mechanisms have been proposed, like i) QSO illumination (e.g., Haiman & Rees 2001; Weidinger et al. 2004), ii) galactic super-winds (e.g., Mori et al. 2004; Wilman et al. 2005), or iii) cold accretion. In the case of a $z=3.15$ blob, discovered by Nilsson et al. (2005), there are no other sources associated with the object going from X-rays (Chandra) to $8 \mu\text{m}$ emission (Spitzer). The blob has a linear extent of about 50 kpc and a typical surface brightness of 4×10^{-4} erg/s/cm 2 , at the source. Moreover, a galaxy of photometric redshift 3.0 is situated at a projected distance of about 40 kpc from the blob, and may, given the uncertainty in the photometric redshift, be physically associated with the blob.

To test whether this blob can be filamentary gas being accreted “cold” onto a companion galaxy, we conducted the following experiment: for a M31 like proto-galaxy we calculated the Ly α surface brightness, in a 100×100 kpc (projected) region centered on the proto-galaxy, of “cooling” radiation only (so all contributions from regions with young stars were removed, as well as all emission, in general, from gas closer than 10 kpc to any star-forming region). The result is shown in Fig.2 (right), at $z \sim 3$, for a period of about 1 Gyr, with time resolution of just 2.5 Myr. As can be seen from the figure, we can get to within about an order of magnitude of the observed surface brightness level. This is interesting, and may point to a cold accretion origin of the blob Ly α emission, just on a larger scale, such as filamentary gas accretion onto a galaxy group – this option is currently being investigated. Given that in a search volume of about 40000 comoving Mpc 3 , only one such blob has been detected, it is actually comforting, that we could *not* reproduce the blob characteristics, by cold accretion onto this, randomly selected, M31 like galaxy.

3. The $z \sim 1$ Tully-Fisher relation

Considerable effort has been spent in recent years to determine the evolution of the zero-point and slope of the disk galaxy Tully-Fisher relation going from $z=0$ to $z \sim 1$ (e.g., Vogt 1999; Barden et al. 2003, Milvang-Jensen et al. 2003; Bohm et al. 2004; Bamford et al. 2005). The observational results span a range from almost no evolution to about 1.1 mag fading in the B band. Such observational information provides important constraints on models of galaxy formation and evolution, in particular no or only very mild evolution points to scenarios with considerable, continuing disk growth, going from $z=1$ to 0.

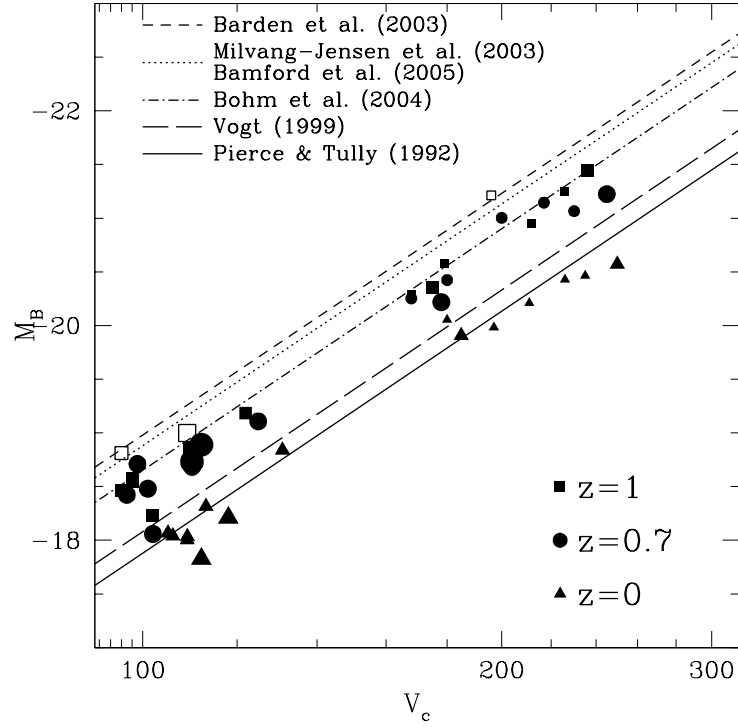


Figure 3. Tully-Fisher relations from observations, as well as, simulations. Solid line: B band $z=0$ TF relation of Pierce & Tully (1992) for Sc galaxies ($B-V \sim 0.55$), shifted downwards by 0.6 mag to enable a comparison to the model disk galaxies which have $B-V=0.6-0.75$ (\sim Sb type). Other lines show the differential evolution of the zero-point of the B-band TF going to $z \sim 1$, reported by various authors (the slopes have been forced to be as for the $z=0$ TF relation). Results of models, invoking feedback, self-consistent treatment of chemical evolution and metal-dependent radiative cooling, and assuming a universal baryon fraction of 0.15 (Portinari & Sommer-Larsen 2005) are shown by various symbols. Filled symbols correspond to $z=0, 0.7$ and 1. Open symbols refer to disk galaxies, which were too disturbed at $z=1$ to enable determination of the TF quantities; hence these were determined at $z=0.8$ instead. Smallest symbols correspond to the original resolution of Sommer-Larsen et al. (2003), medium sized and large to 8 and 64 times higher mass resolution, respectively.

Given this, it is clearly of interest to compare to what fully cosmological galaxy formation simulations, incorporating feedback, non-instantaneous chemical evolution, metal-dependent radiative cooling etc. predict. We have recently engaged in such a study, and show the first results in Fig.3; the full results will be presented in Portinari & Sommer-Larsen 2005. The preliminary conclusion based on the results shown in Fig.3 is that our results for $z=0.7$ and 1.0, relative to the $z=0$ results are nicely bracketed by the various observational

determinations at $z \sim 1$. Moreover, we find that the stellar *mass* TF relation shows essentially no evolution going from $z=1$ to 0, since an increase in stellar mass leads to an increase in V_c as well. This is in agreement with the findings of Conselice et al. (2005).

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